Universität Münster

The Karlsruhe Tritium Neutrino Experiment

V.M. Hannen for the KATRIN collaboration

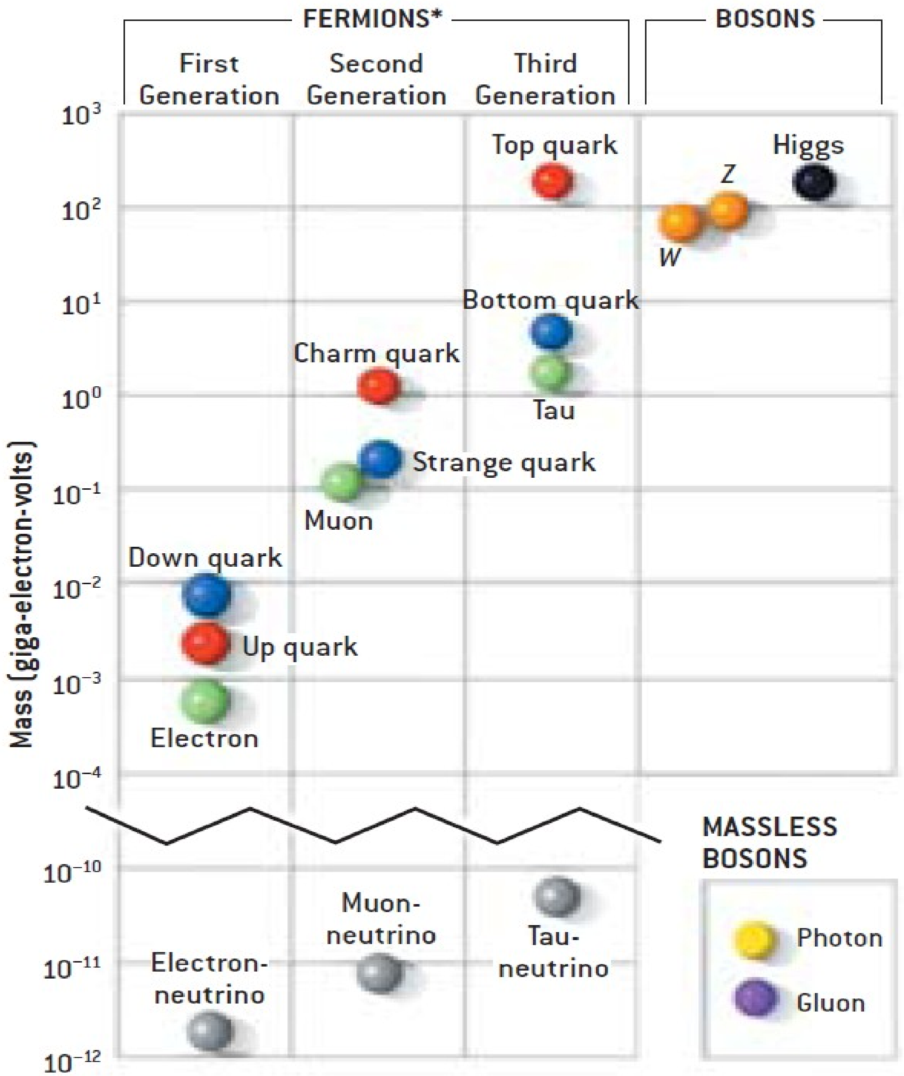
Institut für Kernphysik,
Universität Münster

Neutrino mass in particle physics

- Nature of the neutrino: Majorana or Dirac particle, i.e. is the neutrino it's own anti-particle ?

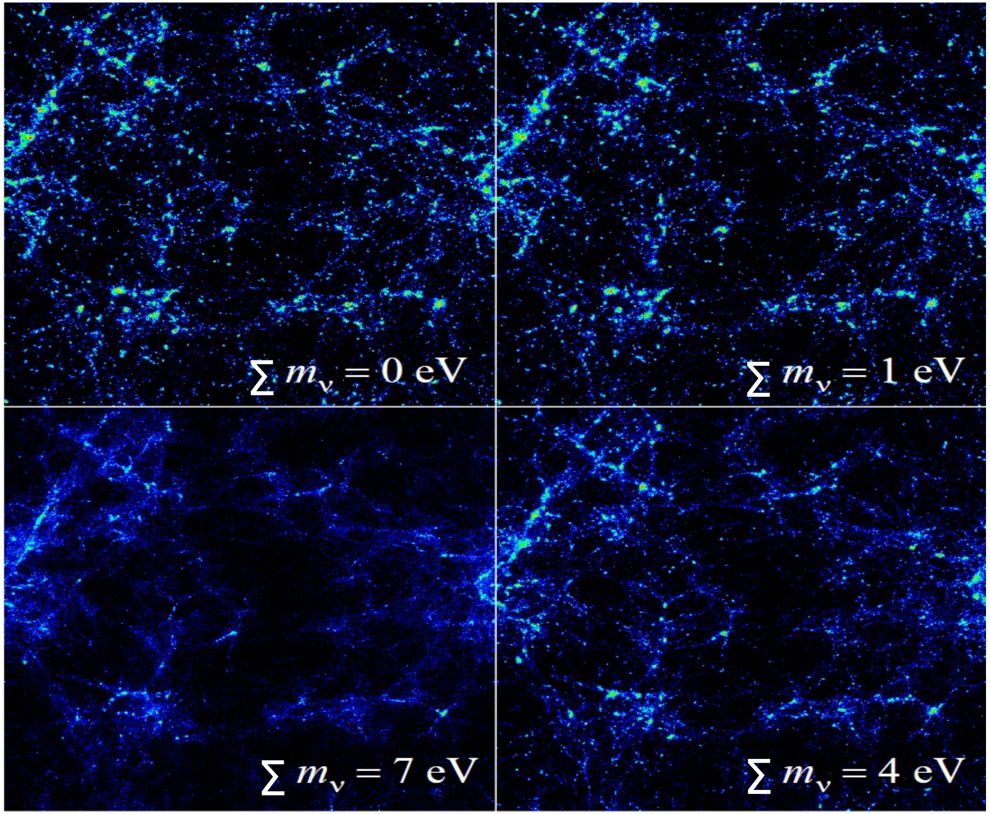
- How to explain the many orders of magnitude difference between neutrino mass limits and masses of the charged fermions of the standard model
  → sea-saw type I and type II mechanisms

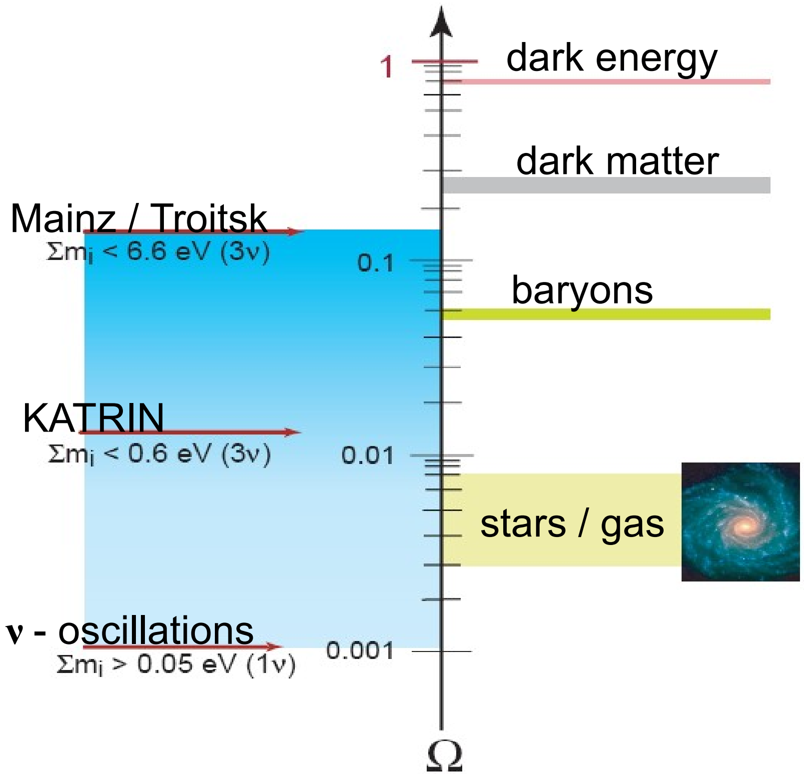
- Possible connection to the generation of the observed matter - antimatter asymmetry in the universe
  → leptogenesis



Neutrino mass in cosmology

- Neutrinos are (after γ's) the second most abundant particle species in the universe
- As part of the hot dark matter, neutrinos have a significant influence on structure formation





- For large Σm_ν values fine grained structures are washed out by the free streaming neutrinos

Chung-Pei Ma 1996

Current knowlegde and open questions

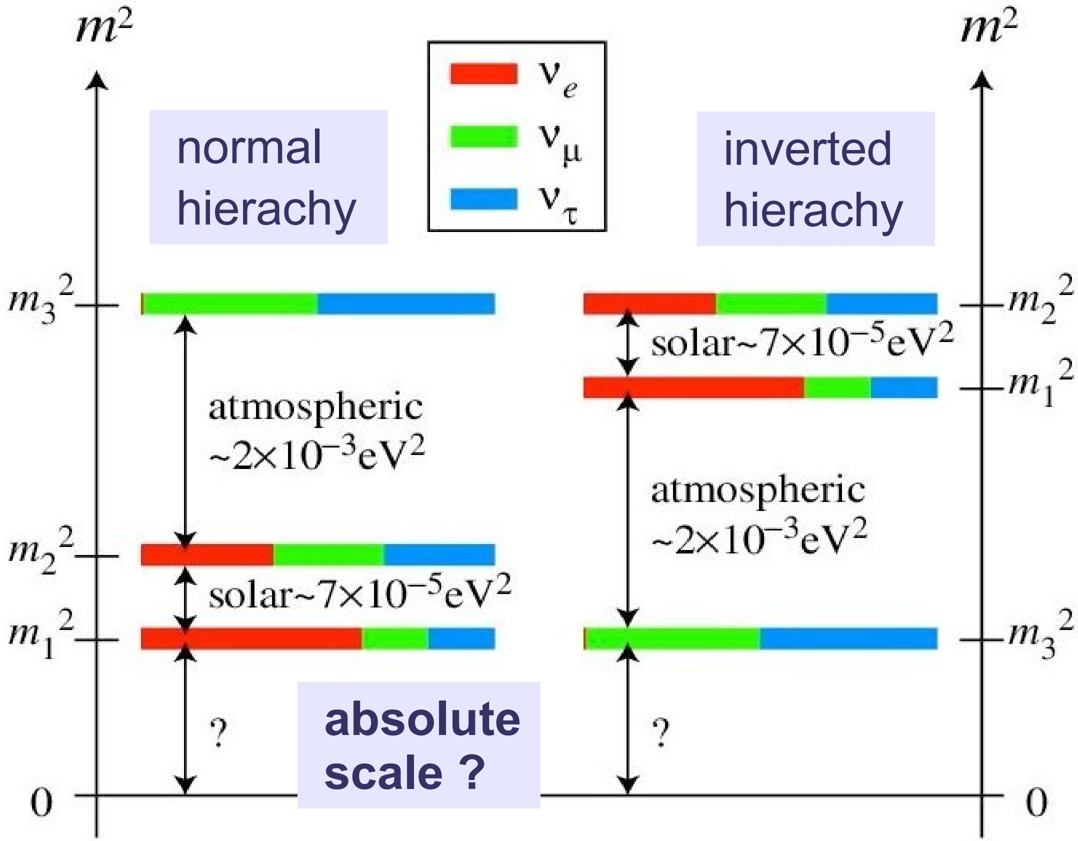
Universität Münster

What we know (from ν oscillations):

- Neutrino flavour eigenstates differ from their mass eigenstates
- Neutrinos oscillate, hence they must have mass
- Mixing angles and Δm^2 values known (with varying accuracies)

What we don't know :

- Normal or inverted hierachy ?
- Dirac or Majorana particle ?
- CP violating phases in mixing matrix ?
- **No information about absolute mass scale !** (only upper limits)
- Existence of sterile neutrinos ?



Search for neutrino mass

β-decay: absolute ν-mass

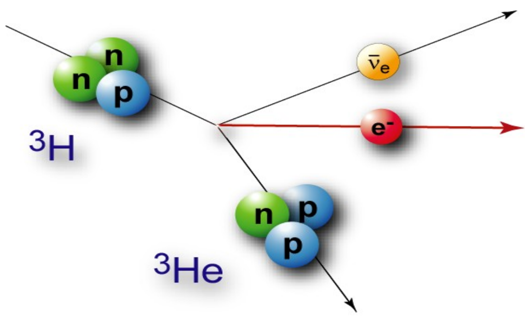
model independent, kinematics

status: $m_\nu < 0.8$ eV

potential: $m_\nu \approx 0.2$ eV

e.g.: KATRIN, Project-8, ECHO HOLMES, NuMECS

$$m_\nu^2 = \sum |U_{ei}{}^2| m_i^2$$



0νββ-decay: eff. Majorana mass

model-dependent (CP-phases)

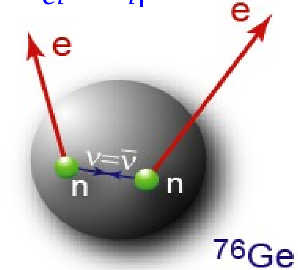
status: $m_{\beta\beta} < 36$ meV to 156 meV

[^{136}Xe, *Phys. Rev. Lett. 130, 051801 (2023)*]

potential: $m_{\beta\beta} \approx 20\text{-}50$ meV

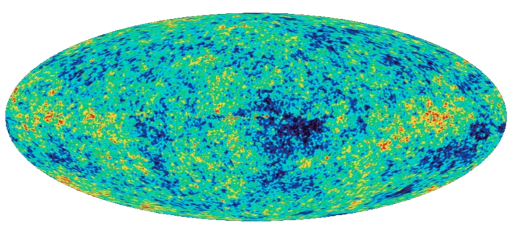
e.g.: KamLAND-Zen, GERDA, CUORE, EXO, SNO+, Majorana, Nemo 3, COBRA

$$m_{\beta\beta} = \left|\sum U_{ei}{}^2 m_i\right|$$



neutrino mass measurements

$$\sum m_i$$

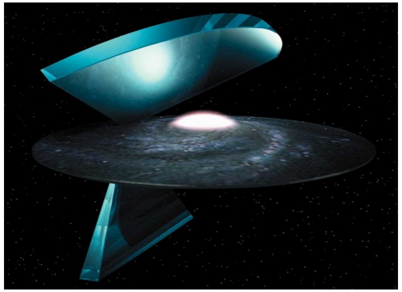


cosmology: ν hot dark matter Ω_ν

model dependent, analysis of CMB and structure formation data

status: $\Sigma m_i < 0.11$ eV

[*Planck PR4 release, A&A, 682 (2024) A37*]



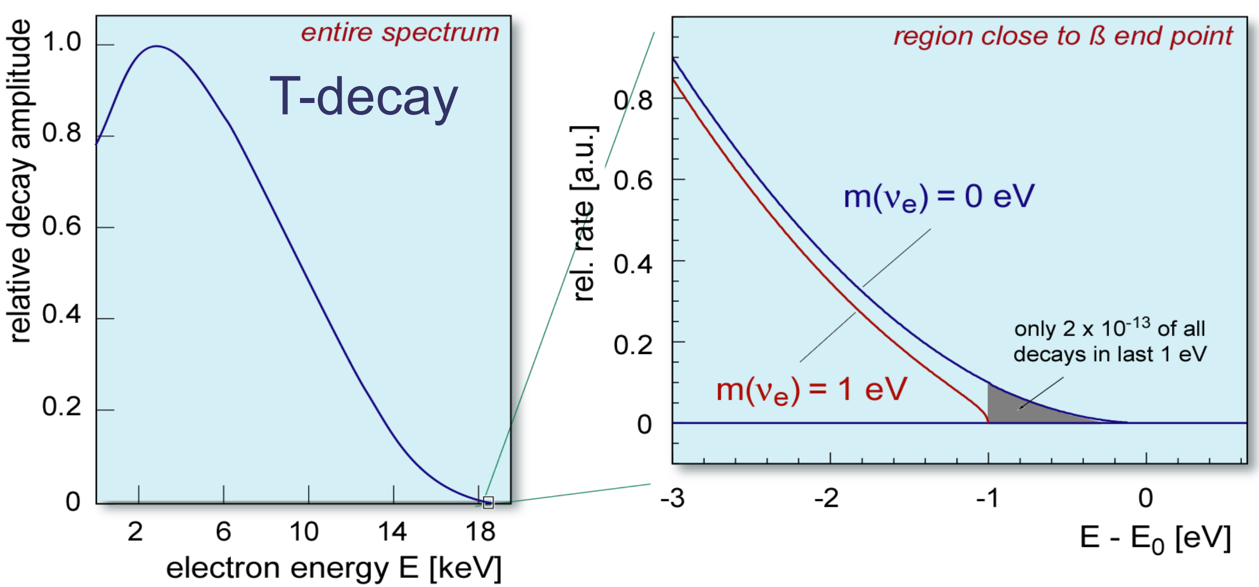
Kinematic determination of $m(\nu_e)$

$$\frac{d\Gamma}{dE} = C\, p(E+m_e)(E_0-E)\sqrt{(E_o-E)^2-m_\nu^2}\,F(Z+1,E)\,\Theta(E_0-E-m_\nu)\,S(E)$$

$$C = \frac{G_F^2}{2\pi^3}\cos^2\theta_C\,|M|^2$$

$$m_\nu^2 = \sum_{i=1}^{3} |U_{ei}|^2 m_i^2$$

(modified by final state distribution, recoil corrections, radiative corrections, ...)



Suitable Isotopes:

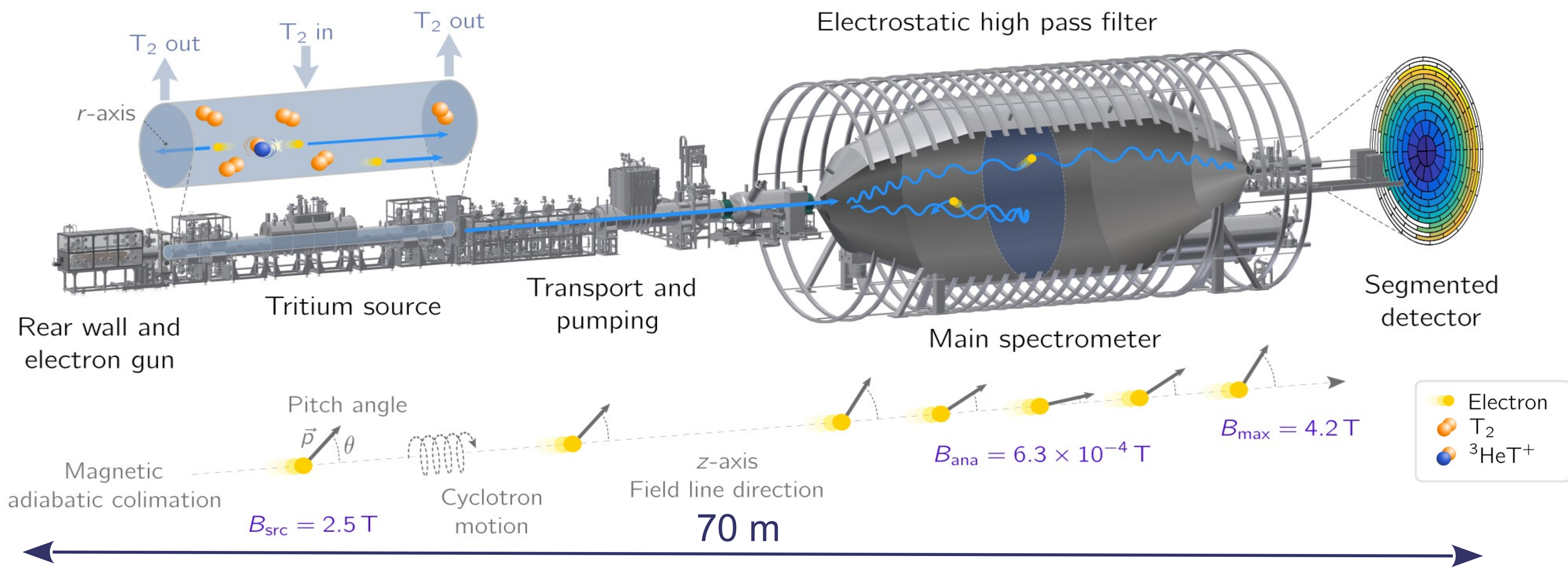
Tritium
- E_0 = 18.6 keV, $T_{1/2}$ = 12.3 a
- S(E) = 1 (super-allowed)

Rhenium
- E_0 = 2.47 keV, $T_{1/2}$ = 43.2 Gy

alternative approach:

Holmium (EC decay)
- Q_{EC} ≈ 2.5 keV, $T_{1/2}$ = 4570 y

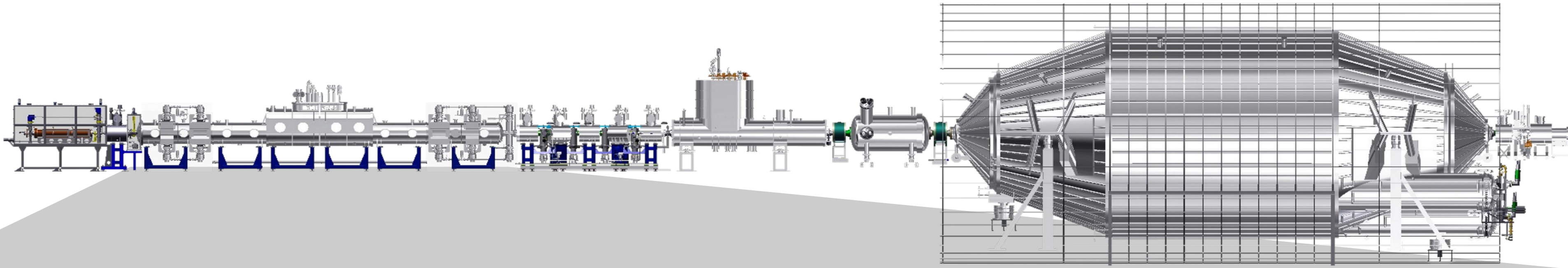
KATRIN experiment at KIT



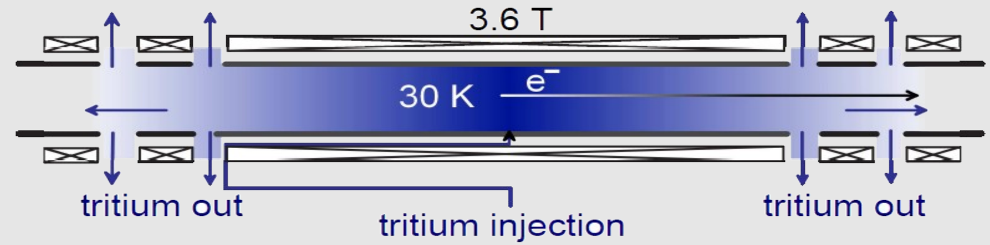
currently not active

leaving

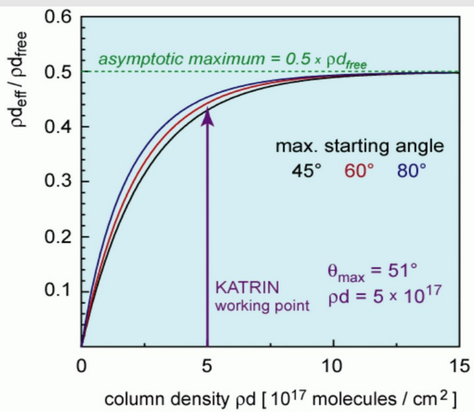
Windowless Gaseous Tritium Source



- beam tube — Ø = 9 cm , L = 10 m
- guiding field — 2.5 T
- Temperature — 80 K ± 0.01 K
- T_2 purity — 95% ± 0.1 %
- column density — $5 \cdot 10^{17}$ T_2/cm^2
- luminosity — $1.7 \cdot 10^{11}$ Bq



- T_2 flow rate — $5 \cdot 10^{19}$ molecules/s (40 g of T_2 / day)

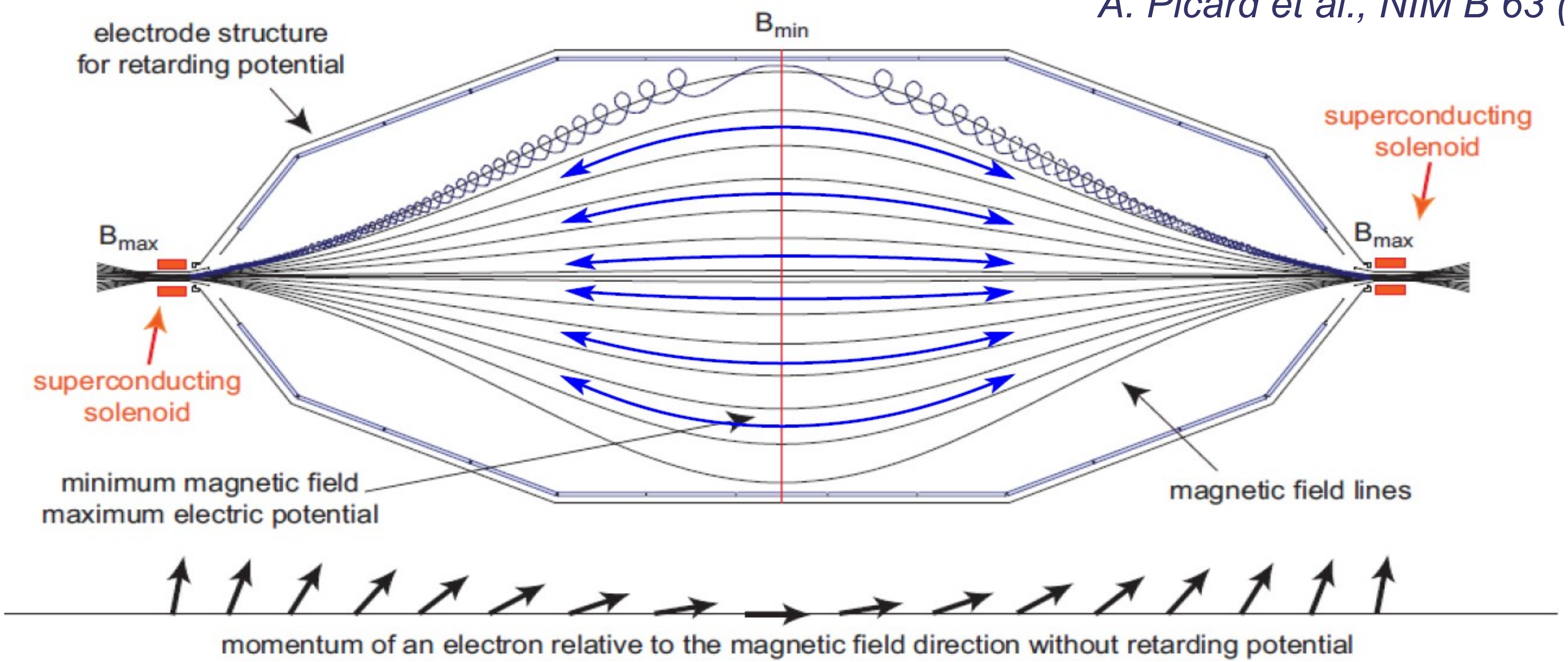


MAC-E filter concept

Universität Münster

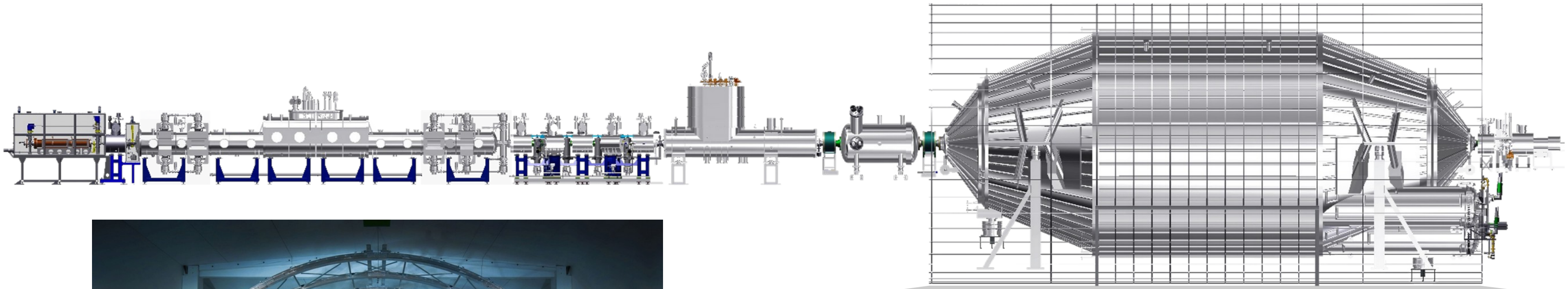
Magnetic Adiabatic Collimation with Electrostatic Filter

A. Picard et al., NIM B 63 (1992)

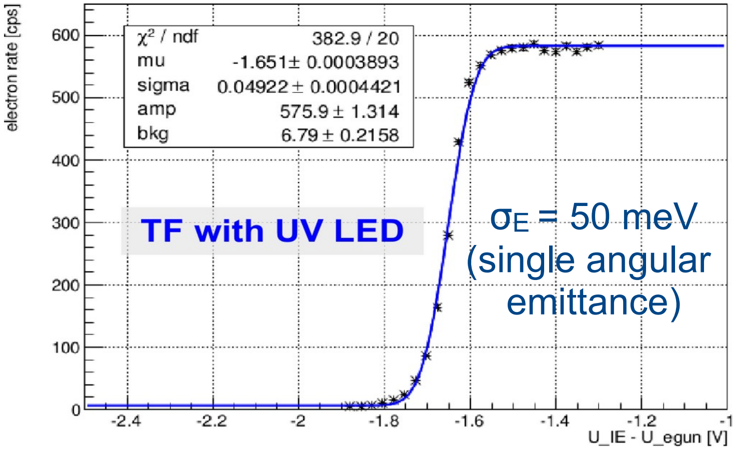


- adiabatic transport → $\mu = E_{\perp} / B = const.$
- B drops by $2 \cdot 10^4$ from solenoid to analyzing plane → $E_{\perp} \rightarrow E_{\parallel}$
- only electrons with $E_{\parallel} > eU_0$ can pass the retardation potential
- Energy resolution $\Delta E = E_{\perp,max,\,start} \cdot B_{min} / B_{max} < 1$ eV

Main-Spectrometer



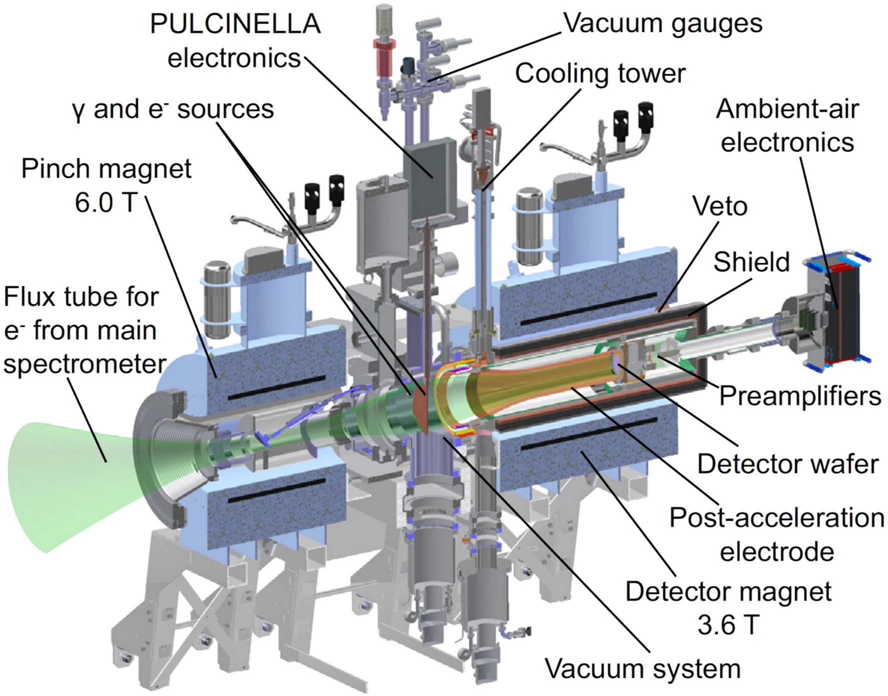
- 18.6 kV retardation voltage, σ < 60 meV
- energy resolution 2.7 eV (SAP mode)
- pressure < 10^{-11} mbar
- Air coils for earth magnetic field compensation
- Double layer wire electrode for background reduction and field shaping

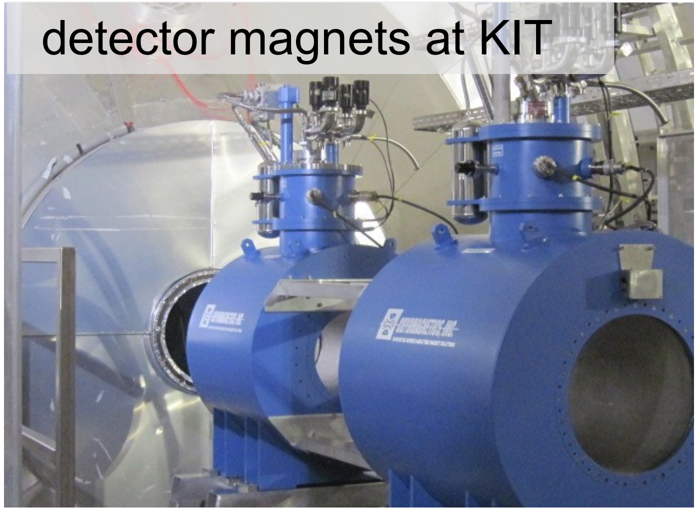


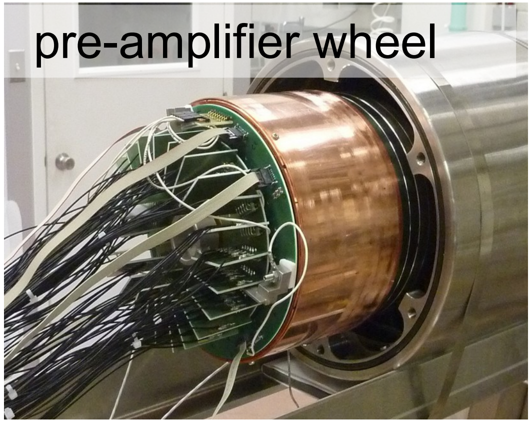
Focal Plane Detector

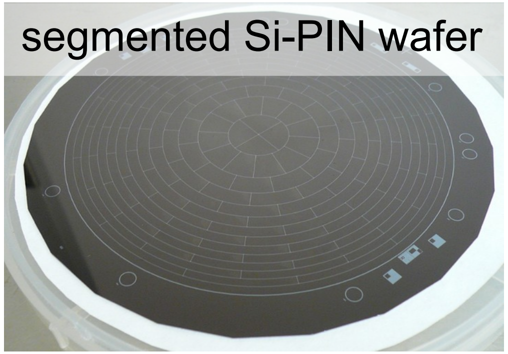
Focal plane detection system

- segmented Si PIN diode: 90 mm Ø, 148 pixels, 50 nm dead layer
- energy resolution ≈ 1 keV
- pinch and detector magnets up to 6 T
- 10 kV post acceleration
- active veto shield




detector magnets at KIT

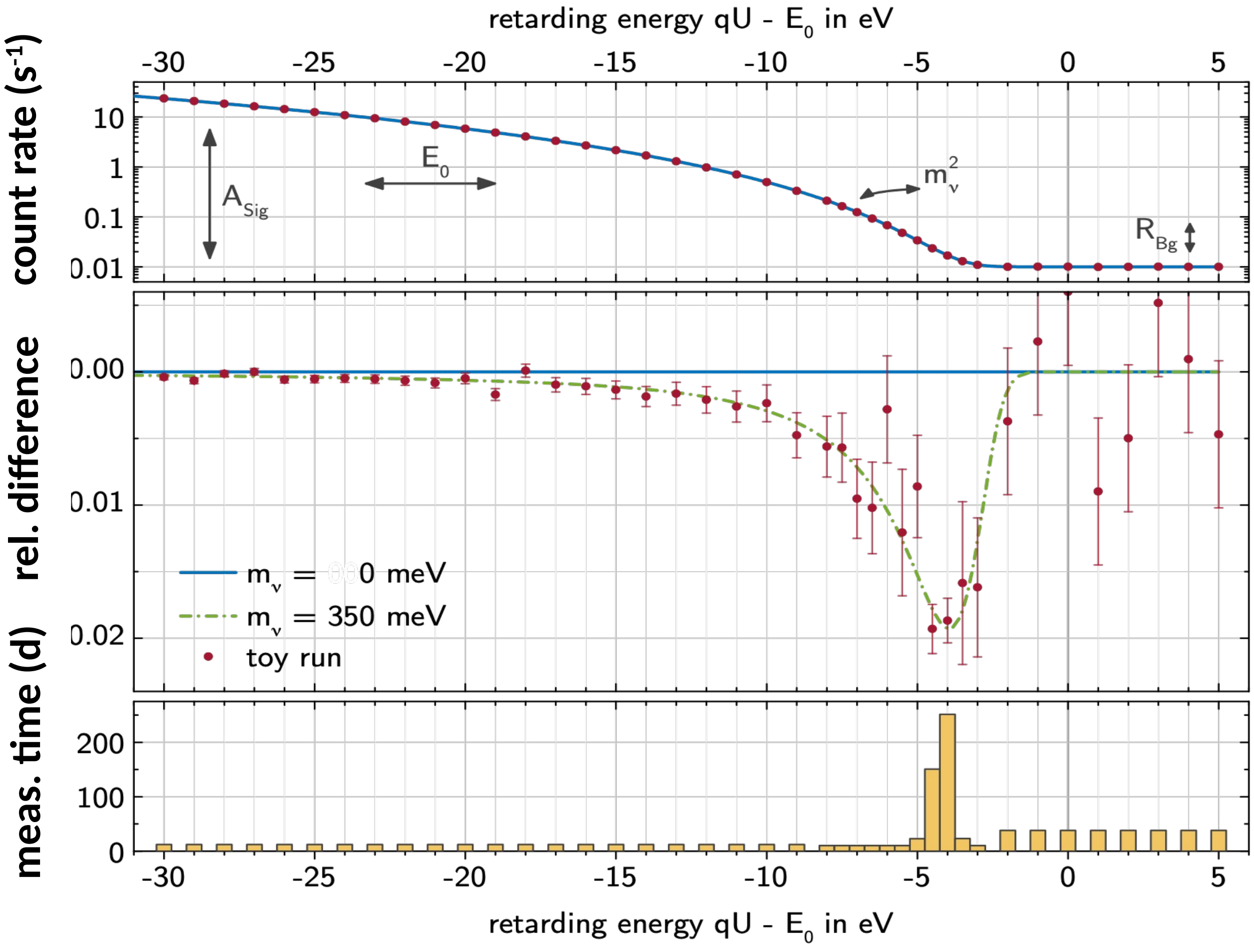

pre-amplifier wheel


segmented Si-PIN wafer

Measurement principle

Universität Münster

- Direct **shape** measurement of **integrated β spectrum**



Four fit parameters:

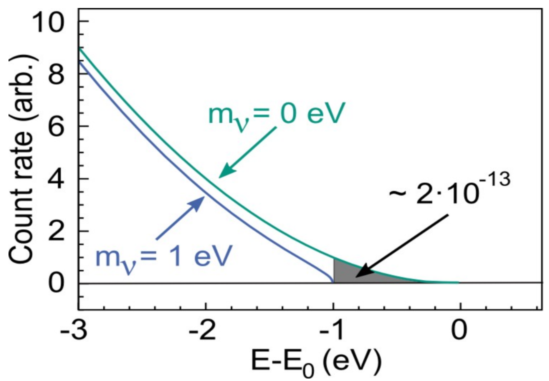
- spectrum ampl. **A_{sig}**
- spectrum endpoint **E_0**
- background rate **R_{bg}**
- squared mass **m^2_ν**

~10^{-8} of all β-decays in scan region ~40 eV below endpoint

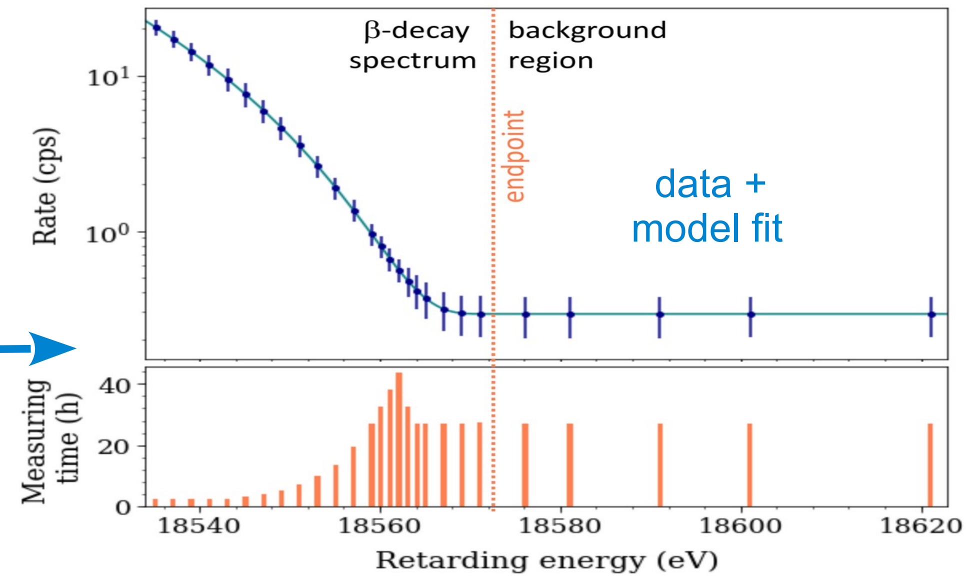
Eur. Phys. J. C 79 (2019) 204

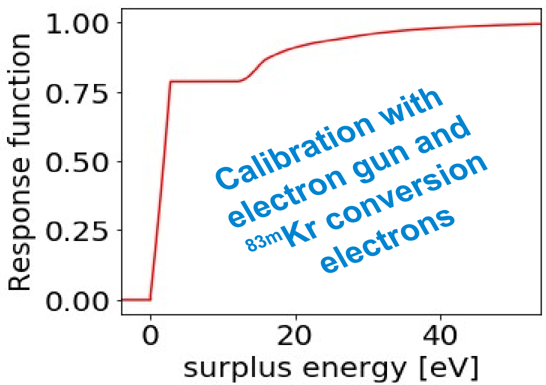
Model of the experimental spectrum

Beta spectrum: **$R_\beta(E, m^2(\nu_e))$**



KATRIN β-scan





Experimental response: **$f(E-qU)$**

$$R(qU) = A_s \cdot N_T \int_{qU}^{E_0} R_\beta(E, m^2(\nu_e)) \cdot f(E-qU)\, dE + R_{bg}$$

PRL 123 (2019) 221802, EPJ C 79 (2019) 204
+ detailed analysis PRD 104 (2021) 012005
+ energy loss measurement EPJ C 81 (2021) 579

Extracted neutrino mass limits

Universität Münster

1st campaign (spring 2019)

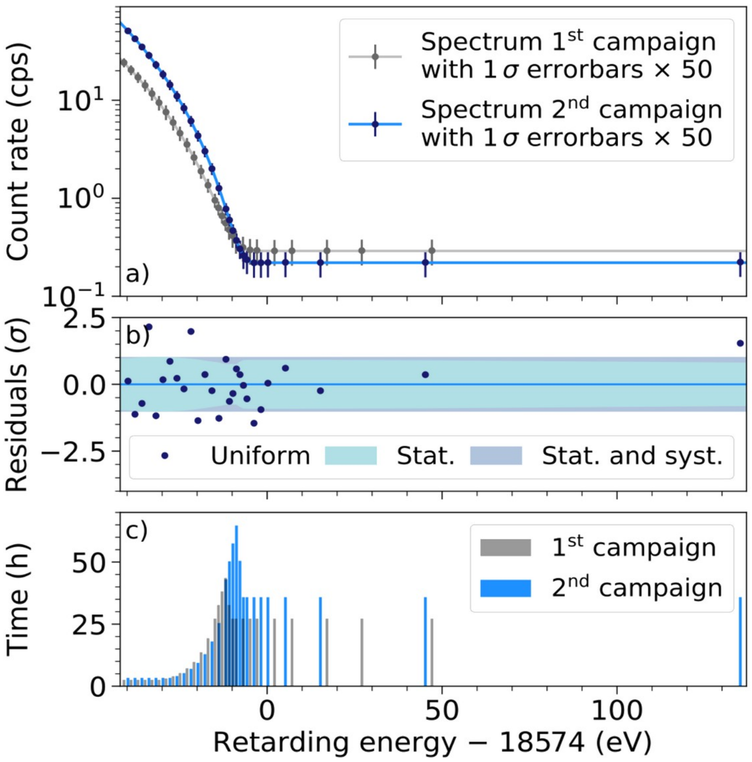
- total statistics: 2 million events
- best fit result: $m_\nu^2 = -1.0^{+0.9}_{-1.1}\ \mathrm{eV}^2$
- mass limit: $m_\nu < 1.1\ \mathrm{eV}\ (90\,\%\,CL)$

2nd campaign (autumn 2019)

- total statistics: 4.3 million events
- best fit result: $m_\nu^2 = 0.26^{+0.34}_{-0.34}\ \mathrm{eV}^2$
- mass limit: $m_\nu < 0.9\ \mathrm{eV}\ (90\,\%\,CL)$

Combine 1st and 2nd campaign:

- mass limit: $m_\nu < 0.8\ \mathrm{eV}\ (90\,\%\,CL)$

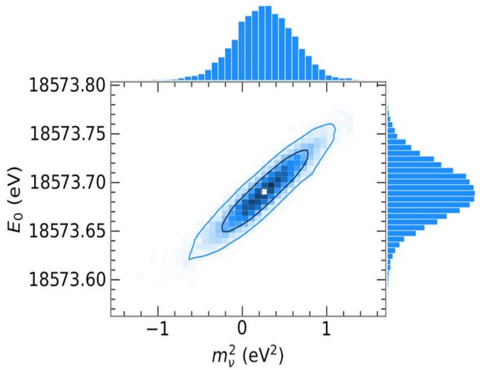


Cross-check: endpoint energy

E_0 = 18573.69 ± 0.03 eV → Q-value: 18575.2 ± 0.5 eV

→ good agreement with Penning trap experiments:

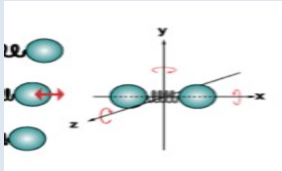
Q = 18575.72 ± 0.07 eV *PRL 114 (2015) 013003*



Nature Physics 18 (2022) 160

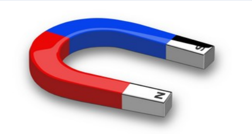
Main systematic uncertainties

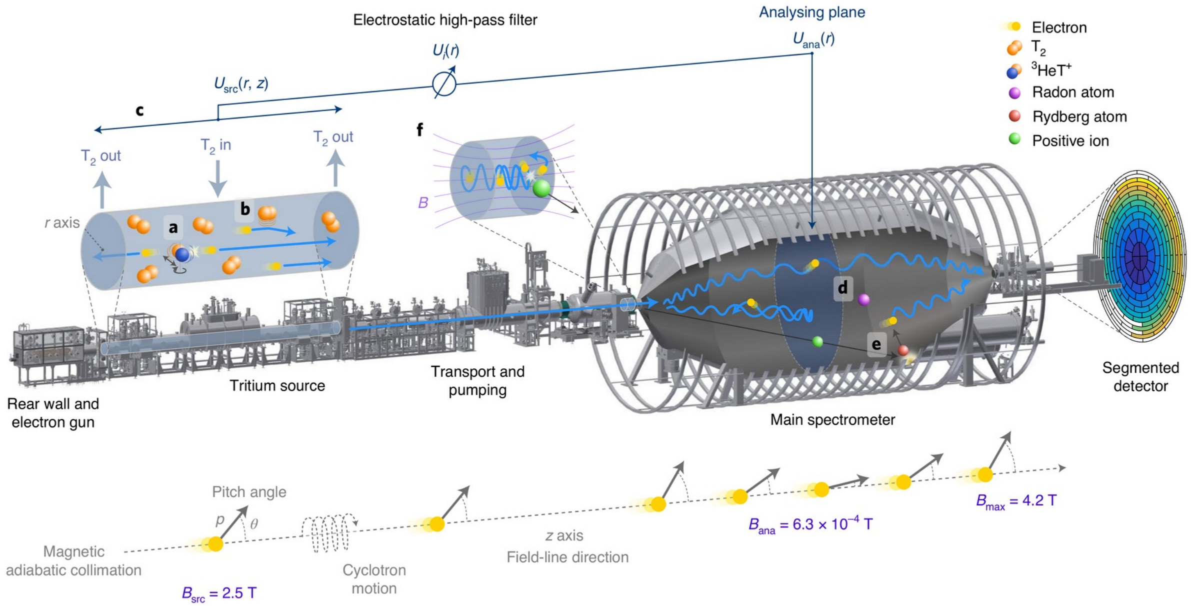
Molecular final states
- Quantum-chemical computations

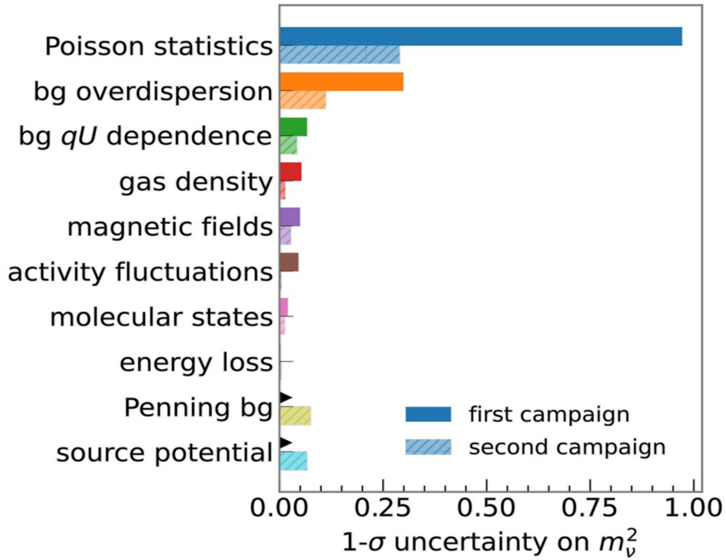


Source electric potential
- plasma properties
- surface conditions

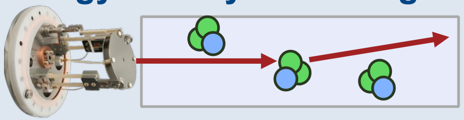
Magnetic fields
- source
- spectrometer
- detector







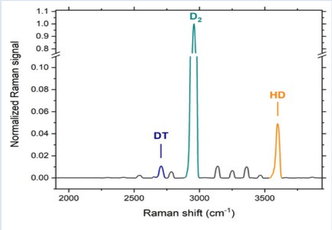
Energy loss by scattering



EPJ C 79 (2019) 204
EPJ C 81 (2021) 579

Activity fluctuations
- column density
- Tritium purity (T_2, DT, HT)

Sensors 20 (2020) 4827



Background
- Volume dependent "Rydberg" background
- Voltage dependent background
- Time structure due to trapped electrons

JINST 13 (2018) T10004
Eur. Phys. J. A 44 (2010) 499
Astropart. Phys. 138 (2022) 102686

Background sources

Main sources of background electrons originating inside or between the spectrometers:

- Time-dependent background due to inter spectrometer Penning trap
- Non-poissonian distributed background due to stored electrons from Radon decays
- Volume dependent background from ionization of Rydberg states created by radioactive decays on the inner vessel surface

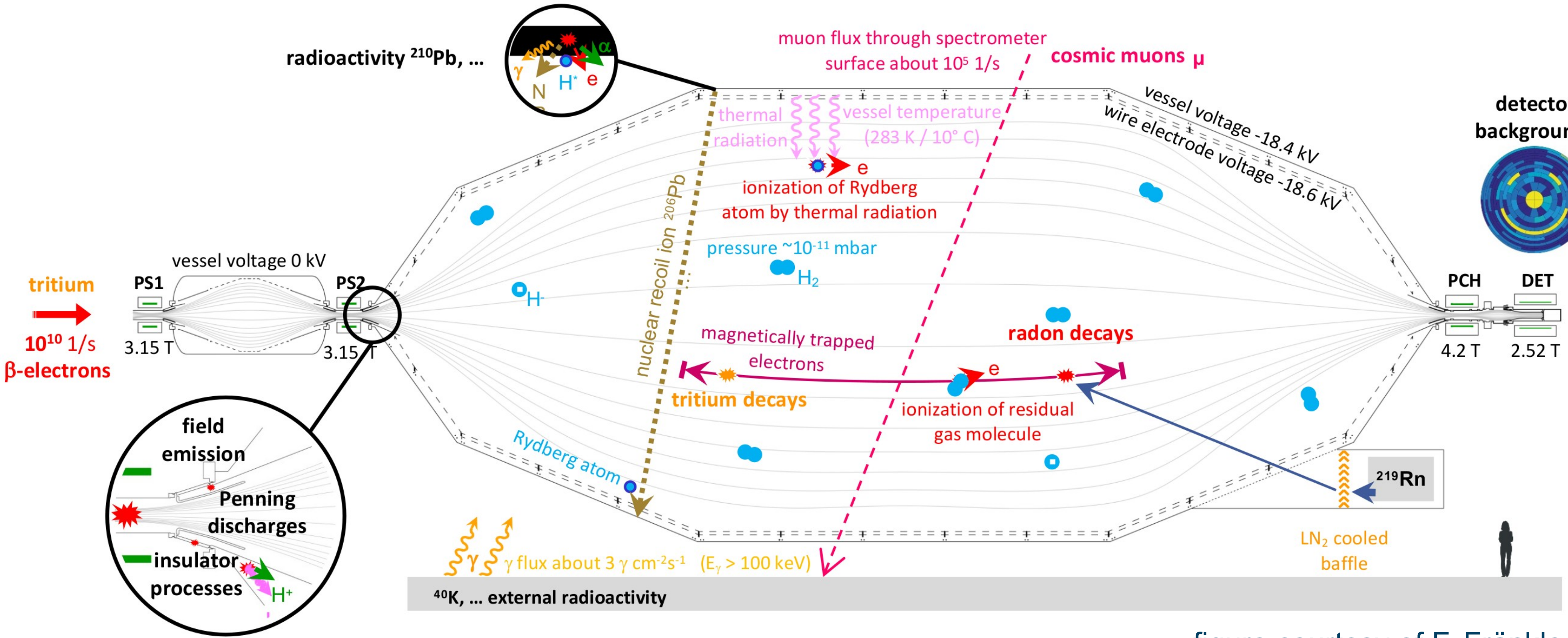
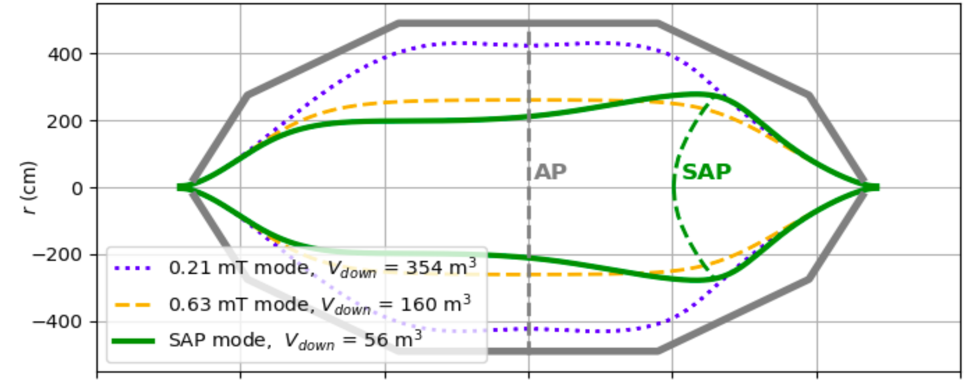


figure courtesy of F. Fränkle

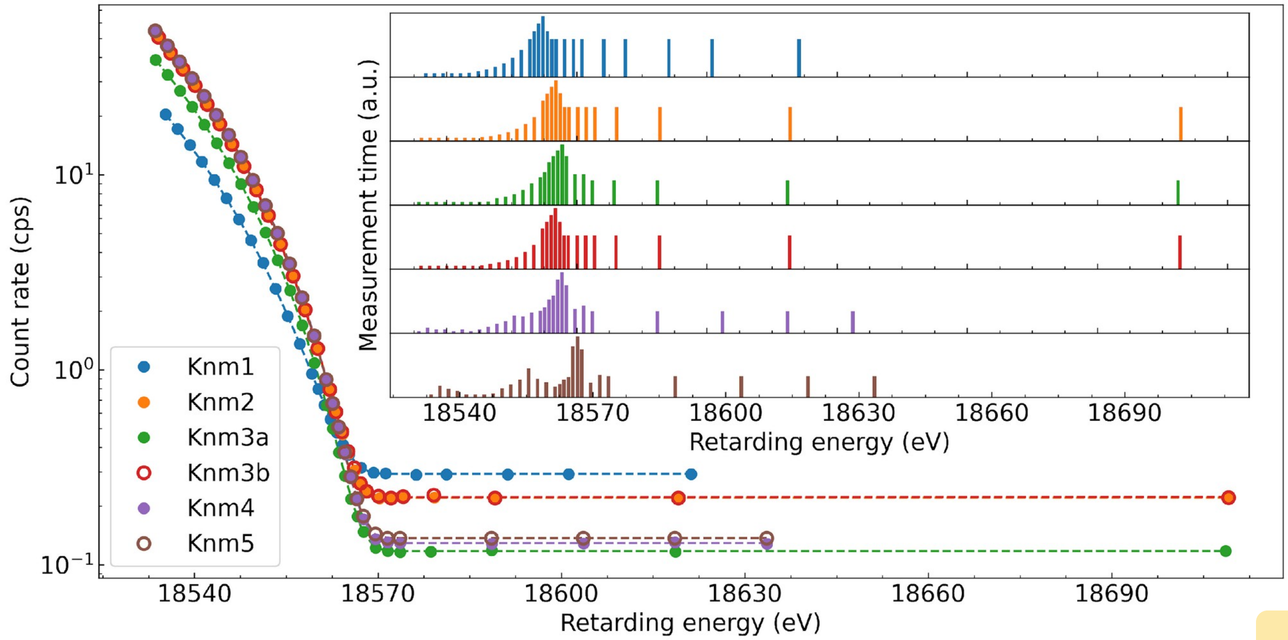
Reduction of experimental backgrounds

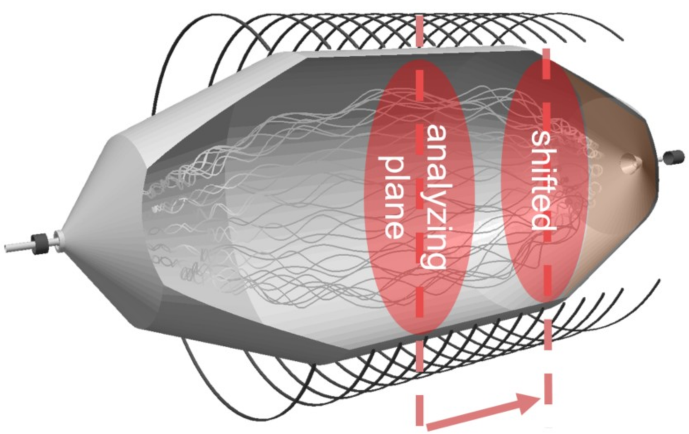
Universität Münster

- Reduction of radon related backgrounds by LN_2 baffles
- Removal of inter-spectrometer Penning trap to eliminate background time dependence
- New spectrometer field configuration (shifted analysis plane) reduced background by factor 2 and removes non-poissonian backgrounds



Eur. Phys. J. C 82 (2022) 258

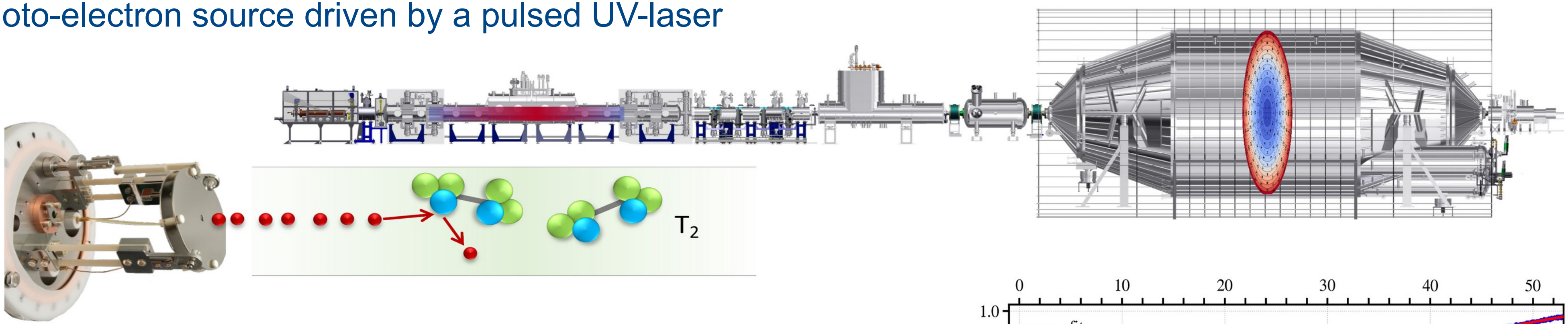




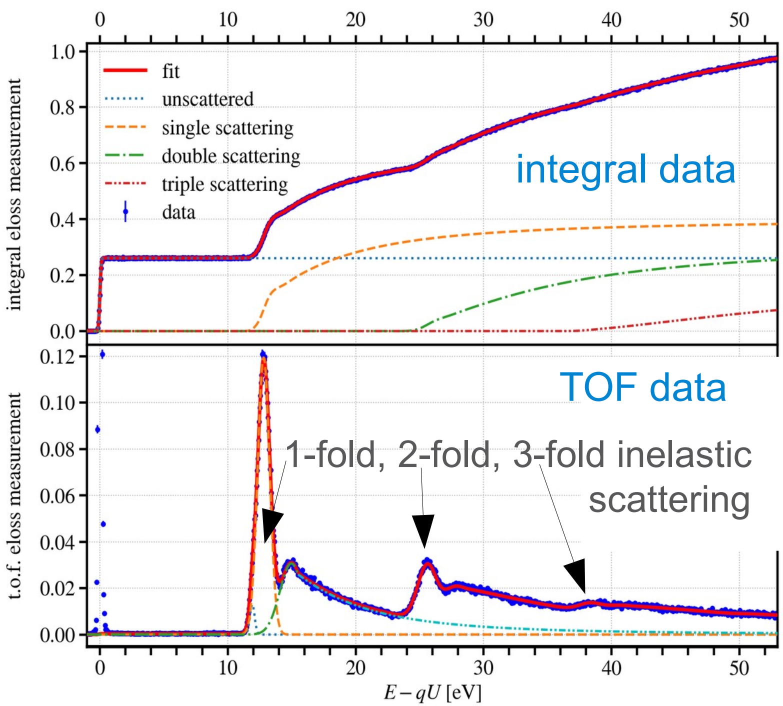
see Talk by Joscha Lauer, Mo. 15:00

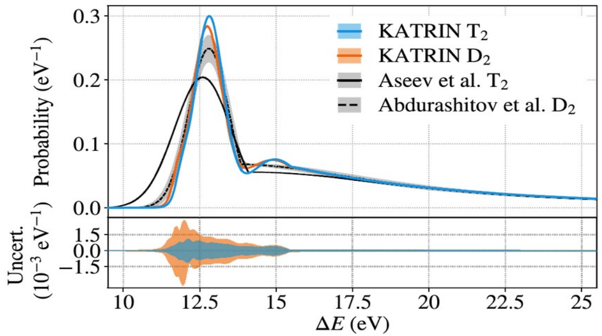
Response function measurement

- Determination of the experimental response function using a mono-energetic, angular selective photo-electron source driven by a pulsed UV-laser



- Measurement of integral and differential (using TOF method) spectra at different column densities
  → Extraction of spectrometer transmission function and energy losses due to scattering



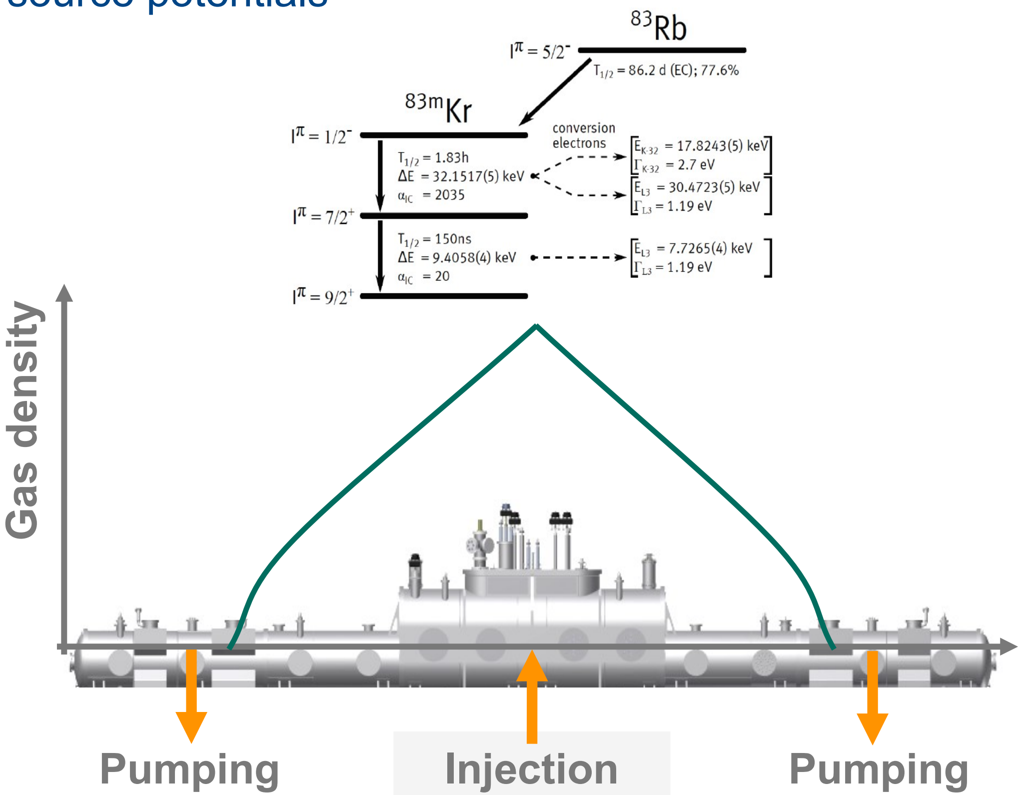


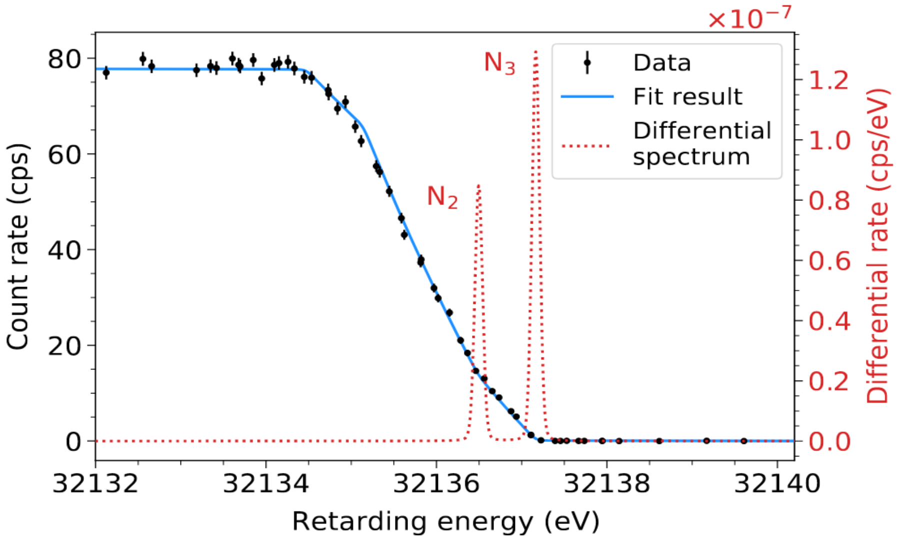
Extract differential energy loss function

EPJ C 81 (2021) 579

Improving source related systematics

- Data of 2020 krypton run at 40% tritium column density used to constrain systematics in 2nd campaign
- Since then: New operation mode with stable co-circulation of tritium and ^{83m}Kr at 80 K at high column density for simultaneous monitoring
- From summer 2021 on: calibration with high intensity (10 GBq) gaseous ^{83m}Kr source to map out source potentials





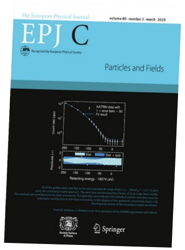
J. Phys. G 47 (2020) 065002

see Talk by Benedikt Bieringer, Fr. 10:45

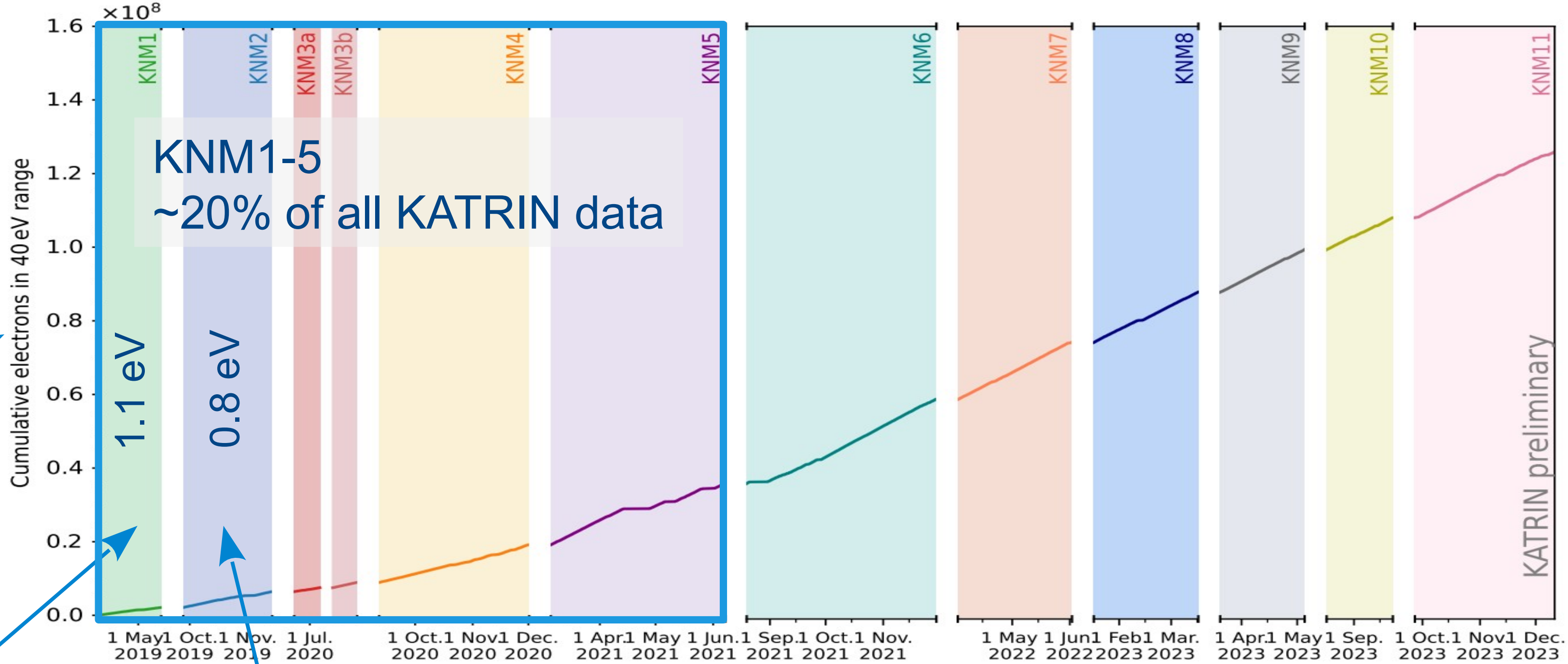
KATRIN data taking

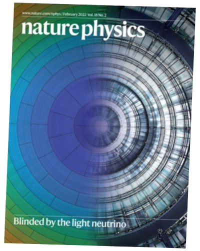
Universität Münster

First tritum run



EPJC 80 (2020) 264





Light sterile neutrinos

+ 

Relic neutrinos

+ 

PRL 123 (2019) 221802 *Nat. Phys. 18 (2022) 160* *PR D 105 (2022) 072004* *PRL 129 (2022) 011806*

Next analysis release

Combined analysis of first five campaigns

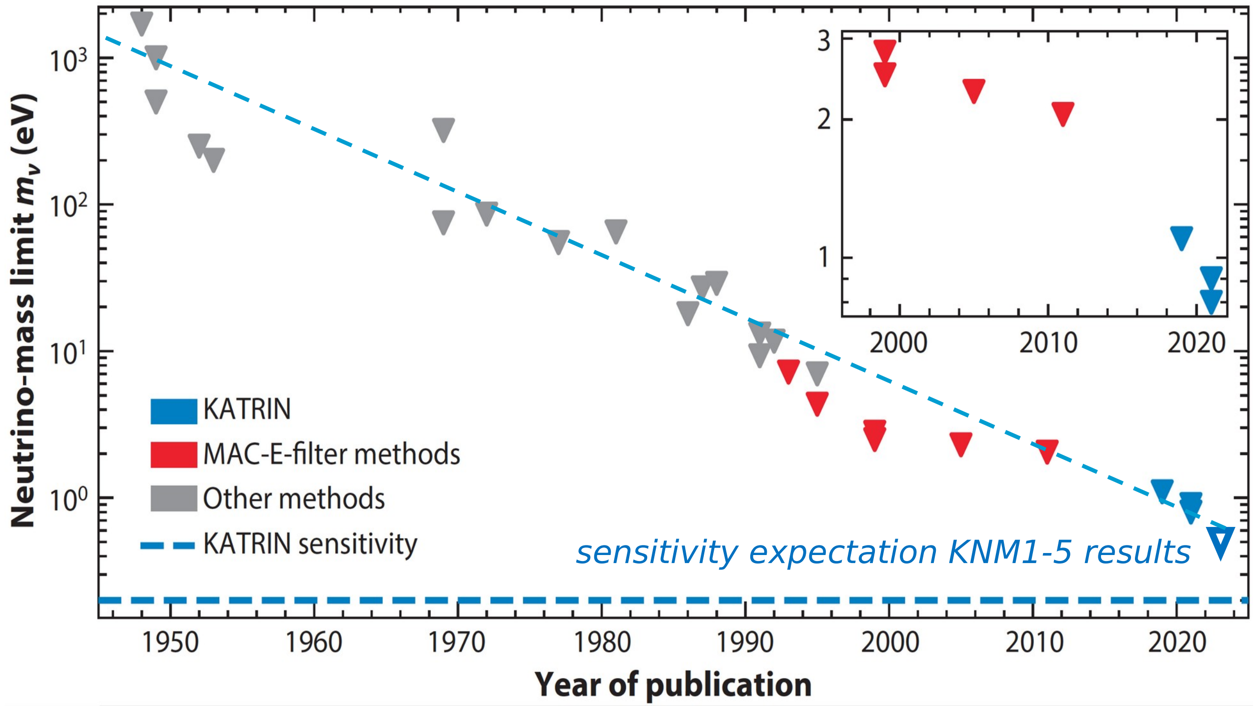
- Currently in unblinding process
- Next data release in summer

Sensitivity projection KNM1-5

- $m_\nu \leq 0.5 \text{ eV } (90\,\%\,CL)$

Improvements:

- Factor six in statistics
- Background reduction
- More accurate knowlegde of systematics



Annu. Rev. Nucl. Part. Sci. 72 (2022) 259

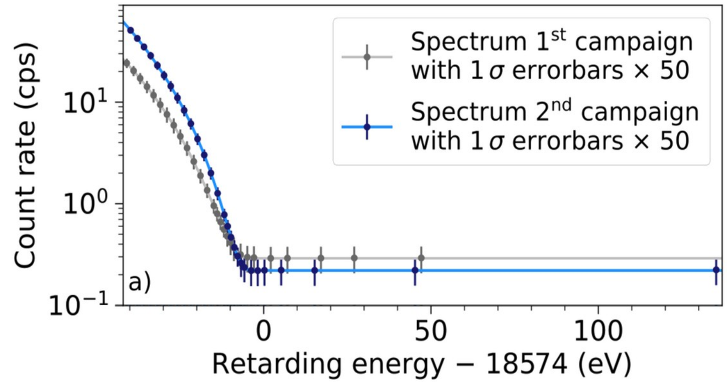
Contiunation of current measurement programm until end of 2025

- collect 1000 days of beta scans
- expect to reach sensitivity $m_\nu < 0.3 \text{ eV } (90\,\%\,CL)$

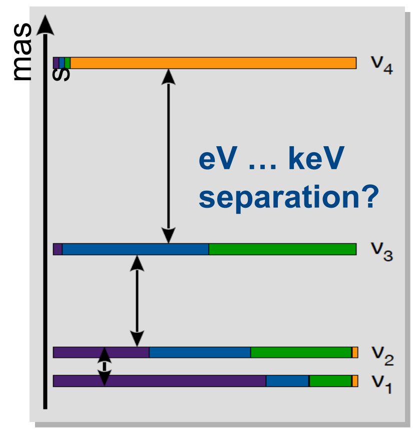
More on analysis methods: talk by Weiran Xu, Thu. 16:00

Beyond neutrino mass searches

Universität Münster



Is there a fourth (sterile) neutrino?



Neutrino mixing: "Kink" in normal β-spectrum (eV scale) or deep β-spectrum (keV scale)

Phys. Rev. D ***105*** *(2022) 072004*
Phys. Rev. Lett. ***126*** *(2021) 091803*
JCAP02 *(2015) 020*

High statistics, high precision β spectrum

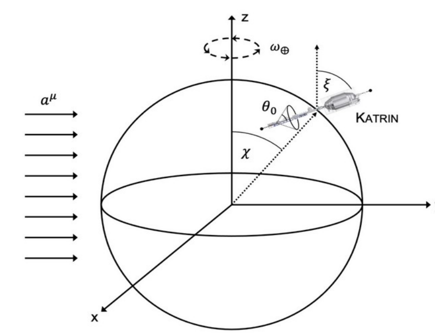
Constrain local over-density of cosmic relic neutrinos (peak search)

PRL 129 (2022) 011806

Search for exotic weak interactions (spectrum shape)

JHEP01 (2019) 206
PoS DISCRETE2022 (2024) 011

Search for Lorentz invariance violation (sidereal modulation)



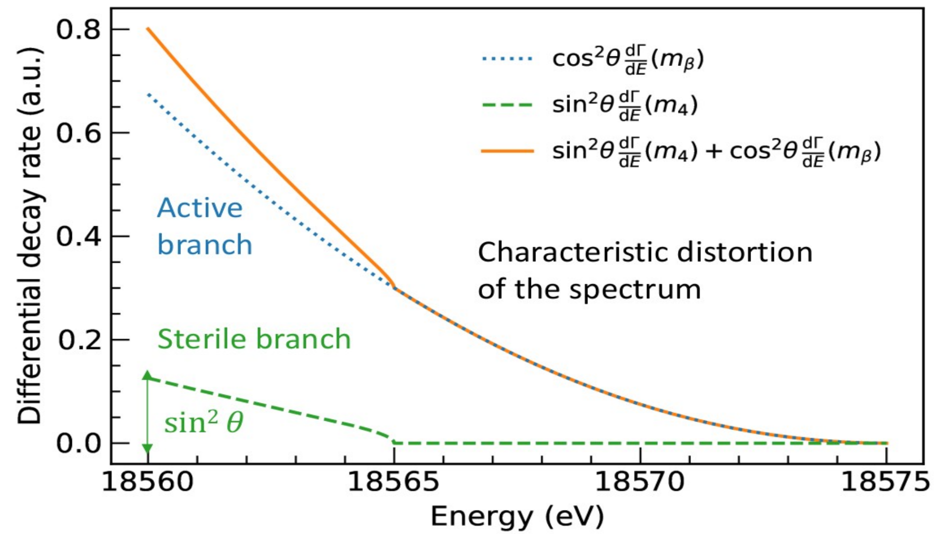
Phys. Rev. D **107** (2023) 082005

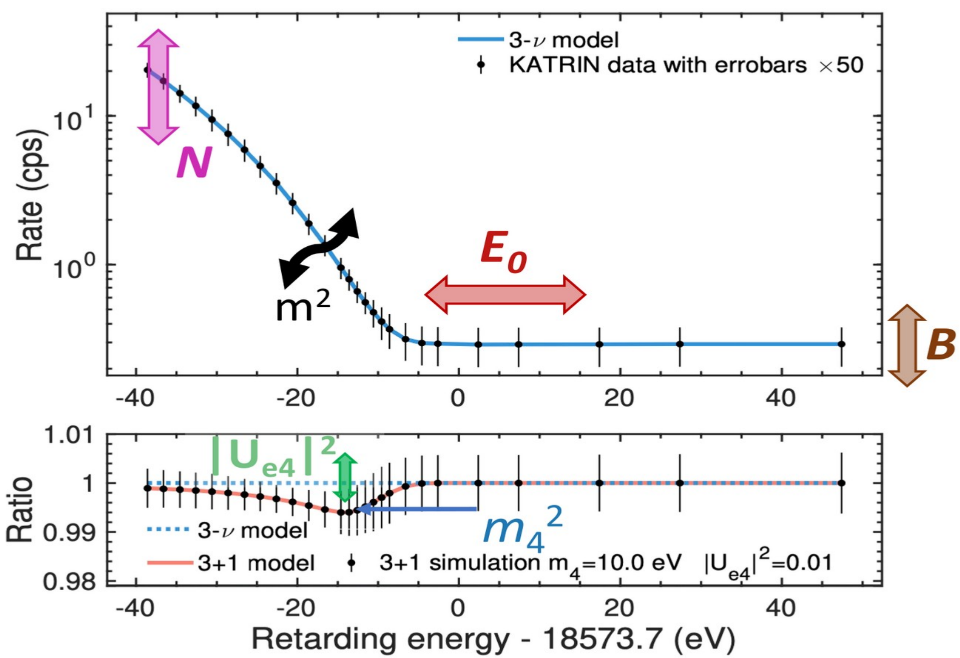
(Light) sterile neutrino signature

Universität Münster

- 3+1 sterile neutrino model
- Same data-set as for the neutrino mass
- Grid search in m_4, $|U_{e4}|^2$ plane

$$\frac{d\Gamma}{dE} = \underbrace{\left(1-|U_{e4}|^2\right)\frac{d\Gamma}{dE}(m_\beta^2)}_{\text{light neutrino}} + \underbrace{|U_{e4}|^2\frac{d\Gamma}{dE}(m_4^2)}_{\text{heavy neutrino}}$$





6 Fit Parameters:

m^2	- neutrino mass (free/constrained)
E_0	- endpoint
N	- amplitude
B	- background rate
m_4^2	- 4th neutrino mass
$\lvert U_{e4}\rvert^2$	- 4th neutrino mixing

Limits on light sterile neutrinos

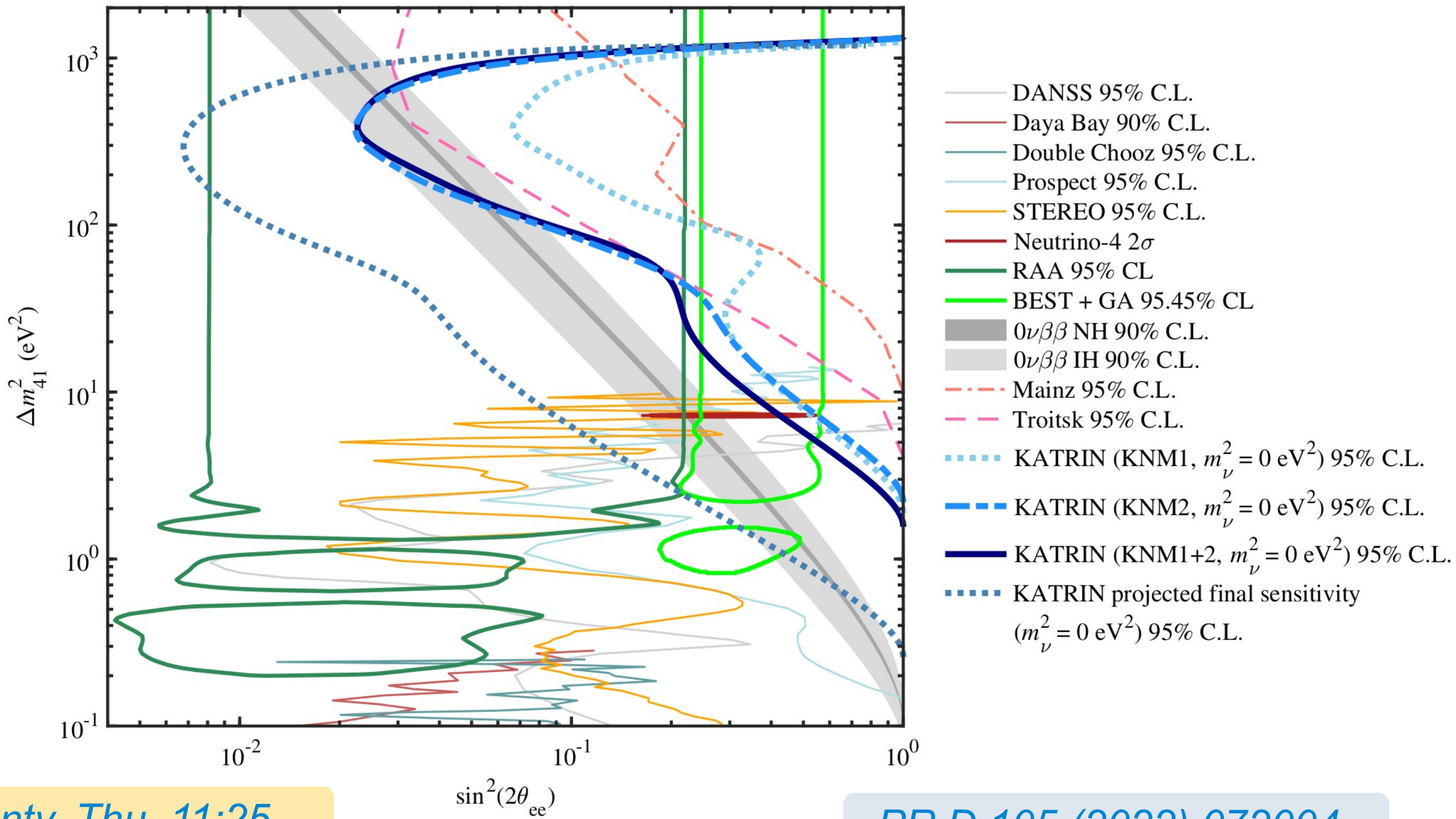
Current dataset

- KATRIN starts to probe very interesting parameter space, complementary to oscillation searches
- approaching the BEST allowed regions with **$\Delta m_{41}^2 > 10$ eV²**

Final dataset

- Probing large portion of RAA, BEST and Neutrino-4 allowed regions
- comparable sensitivity to neutrinoless double β-decay

$$\sin^2(2\theta_{ee}) = 4|U_{e4}|^2(1-|U_{e4}|^2)$$



see Talk by Shailaja Mohanty, Thu. 11:25

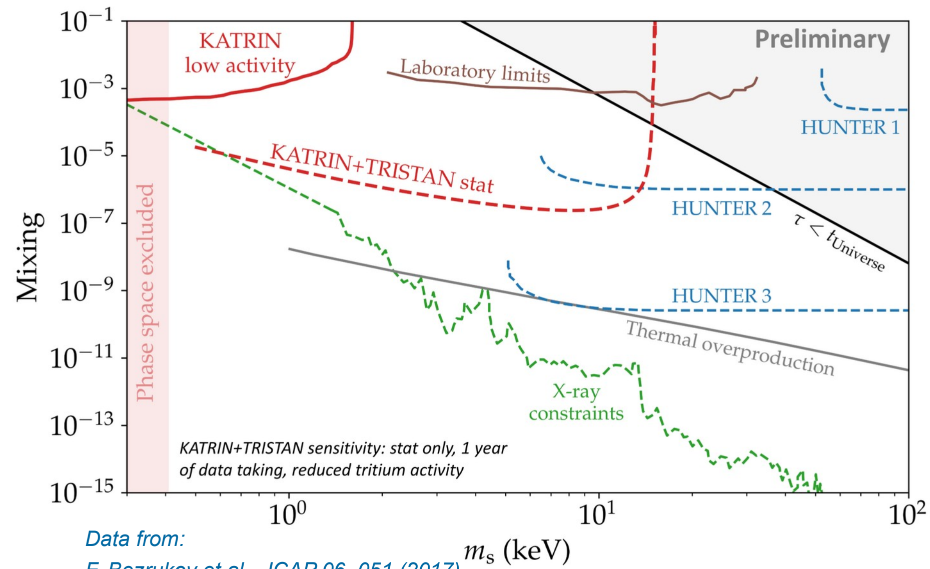
PR D 105 (2022) 072004

Future plans: keV scale sterile neutrinos

Universität Münster

keV-scale sterile neutrino search:

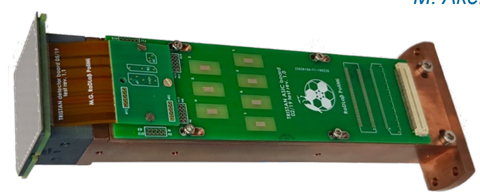
- sterile neutrinos on keV-scale are a viable candidate for dark matter in the universe (WDM)
- First scans deep into the β-spectrum during FT campaign at 0.5% c.d. *arXiv:2207.06337v1 (2022)*
- high-sensitivity search requires new high-rate detector system (TRISTAN) to handle huge electron rates from WGTS over large spectral range

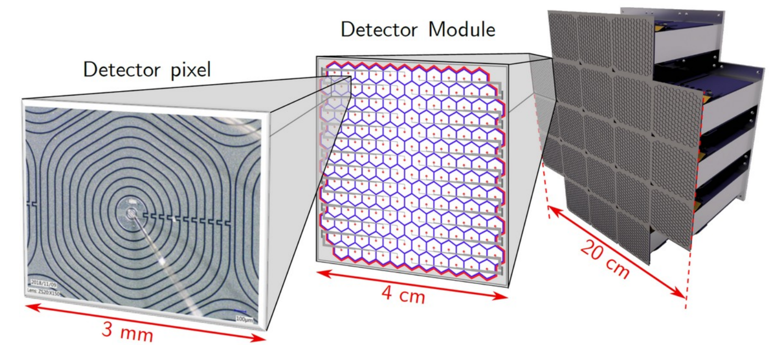


Data from:
F. Bezrukov et al., JCAP 06, 051 (2017)
J. N. Abdurashitov et al., JETP Letters 105, 12 (2017)
F. Benso et al., Phys. Rev. D 100, 115035 (2019)
C. J. Martoff et al., Quantum Sci. Technol. 6 024008 (2021)
S. Friedrich et al., Phys. Rev. Lett. 126, 021803 (2021)
M. Aker et al. , arXiv:2207.06337 (2022)

TRISTAN project in KATRIN:

- novel multi-pixel Silicon Drift Detector array
- large count rates
- excellent energy resolution
- prototypes installed as monitoring devices @ KATRIN
- target sensitivity: **$\sin^2\theta < 10^{-6}$**



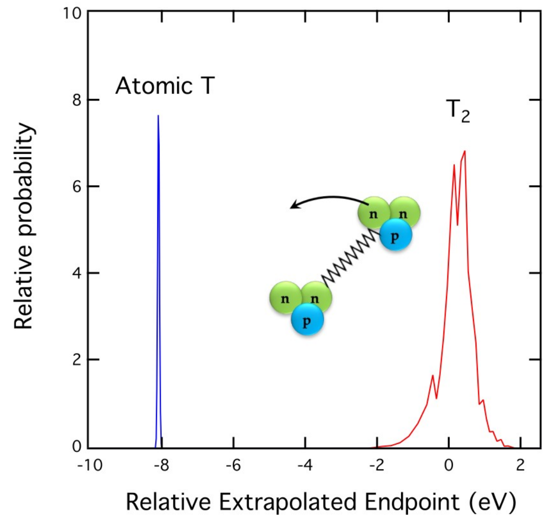


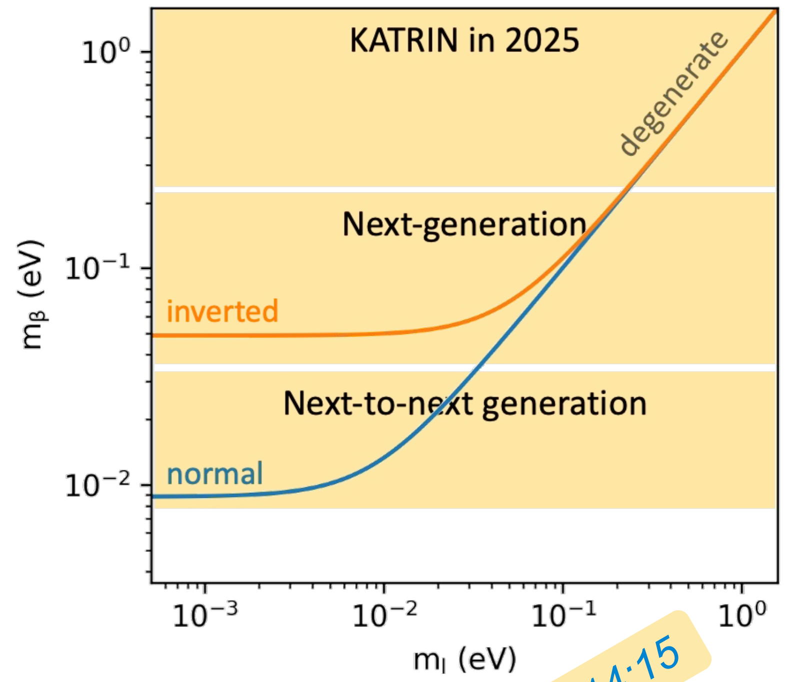
see Talks by Anthony Onillon, Wed. 9:40 and Daniela Spreng, Wed. 10:50

Universität Münster

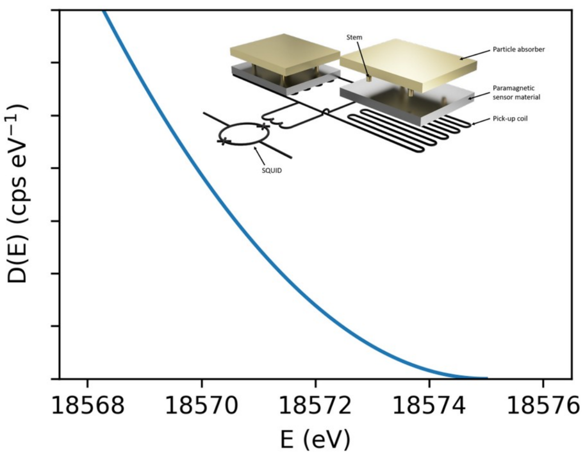
Advancing further with kinematic neutrino mass measurements

- New source concepts: remove spectral broadening due to molecular FSD by going to an atomic tritium source





- Novel detector technologies required for a differential measurement with O(eV) resolution



KATRIN++

see Talk by Magnus Schlösser, Tue. 14:15

Summary

Universität Münster

- Studies of β-decay kinematics offer a model-independent way to determine the neutrino mass, complementary to cosmology and 0νββ searches
- The KATRIN experiment has finalized the analysis of the first two science runs and published the first sub-eV neutrino mass limit with **$m_\nu < 0.8$ eV**
- Several improvements allowed to strongly reduce experimental background and systematic uncertainties
- Analysis of KNM3 to KNM5 science runs ongoing, analysis release expected in summer
- KATRIN has the capability to study several physics topics beyond neutrino mass:
  - eV-scale sterile neutrinos (first upper limits published)
  - keV scale sterile neutrinos (future project with new focal plane detector TRISTAN)
  - upper limit on local relic neutrino overdensity
  - investigations of Lorentz invariance
  - search for exotic weak interactions

Funded by:

Bundesministerium für Bildung und Forschung

HELMHOLTZ GEMEINSCHAFT

DFG

MAX-PLANCK-GESELLSCHAFT

DEPARTMENT OF ENERGY UNITED STATES OF AMERICA

Czech Republic: MŠMT MINISTRY OF EDUCATION YOUTH AND SPORTS

Russian Academy of Sciences Founded in 1724 currently not active